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Experimental characterization and implementation of an integrated autoregressive model to predict the thermal performance of vegetal façades

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ABSTRACT

This article presents the results of an experimental study carried out in a vegetal façade situated in a locality close to Madrid.

The objectives of the study are to develop a performance predictive model of a vegetal façade whose independent variables are irradiance, exterior temperature and relative humidity, based on the effect of the vegetation on the environmental conditions of the building, as well as to characterize thermally the vegetal element by comparing two identical enclosures (with a vegetal layer present in one of them being the only difference).

The results of the three-year monitoring period are analyzed by means of statistical data processing and an autoregressive model is fitted. This model estimates the temperature difference between both enclosures. The validation of the model based on the experimental data is done subsequently.

Once the improvements caused by the vegetation on the interior environmental conditions of the building have been quantified, the results show that it is possible to predict with high accuracy the vegetation's performance, being the multiple *R*-squared of the estimated models around 85%.

Furthermore, the application of the model is suitable for other buildings located in a similar climate to the one studied, as the independent variables exclusively depend on climate conditions.

1. Introduction

The growing interest in vegetal surfaces in both architectural and urban environments is reflected in the gradual development of new research about vegetal façades in recent years [1–8].

In most cases, the studies focus on the analysis of the energy performance of this type of envelopes, as well as the effects stemming from their implementation in buildings and environment, from very different points of view: thermal [9–12] reduction of the urban heat island effect [13–15], air quality [16,17] and acoustic comfort [18].

Generally, these researches tend to base their conclusions on experimental data from monitorings and tests [19,20] or on simulation results [21–23].

In addition, the monitoring periods usually taken into account are short and centered on the summer [19,24], making it impossible to extrapolate the analysis of the treated envelope's performance to other seasons of the year, a necessary condition, in turn, for the study of the building's global thermal balance.

Moreover, simulation software mostly bases the case studies in complex mathematical models [20] which in turn require a comprehensive knowledge of the specific characteristics of the substrate and vegetation for their use [25–27]. A knowledge that, in most cases, is not included in the technical formation of the sector's professionals. The complexity and existence of a great variety of simulation software, testing and monitoring methods, is precisely due to the difficulty in being unable to treat the main components of vegetal façades (water, vegetation and substrate) as any other material. This is due to the fact that vegetation is a living element that interacts with the environment and the building in very different ways, depending on the weather and hydrologic conditions, the type of plant used, etc. [28]. Furthermore, the substrate is composed of several materials whose characteristics differ generally in most cases, affecting significantly the ensemble's behavior. In addition,

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the presence or lack of water affects directly the performance of both the vegetation and the substrate.

In addition to all of this, most researches are focused on the study of the thermal behavior of conventional façades with vegetal elements in their exterior layers [24,29]. Therefore, the results obtained are in general only significant in the study case analyzed, with no possibility of extrapolating the conclusions reached to other situations due to the great amount of variables at play on which the results obtained depend directly: composition and orientation of the enclosure, characteristics of the vegetation and local weather conditions.

Consequently, the option of integrating a vegetal façade in a building isn't usually very feasible for the designer because of the difficulty of predicting the benefits associated to the system, unless there are available data taken under the same conditions of the façade to install.

Once the problems mentioned in the vegetal façades study field have been detected, the ultimate aim of this research contemplates the creation of a flexible tool that allows to predict the thermal performance of certain types of vegetal façades depending on the local weather conditions, as well as enabling the use of aforesaid tool in different contexts than the one studied. To this end, the number of variables at play has been reduced, by choosing a specific type of vegetation (*sedum*), setting the characteristics of the substrate and removing the variables relating to the materials that make up the analyzed envelope, formed exclusively by substrate and vegetation.

The specific objectives pursued are the following: (a) to characterize thermally the vegetal element (substrate plus vegetation) by monitoring two enclosures whose only difference is the vegetation layer existing in one of them; (b) to quantify the effect of the vegetation layer on the thermal conditions in the building's interior during the different seasons of the year; (c) to fit a predictive model for the performance of the vegetal enclosure versus the enclosure without vegetation, whose independent variables would exclusively be the exterior global irradiance, temperature and relative humidity; (d) to validate aforementioned model by using the experimental data obtained from the monitoring of a vegetal envelope during three years.

2. Experimental building and data acquisition

The monitoring took place in Colmenar Viejo 40°39′N, 3°45′W, a locality 40 km North of Madrid, in the Guadarrama mountain range.

In order to have a direct control over the local climate conditions, a weather station is installed next to the experimental building during the monitoring period. The station records data every 15 min, so the resulting mean values of an hour interval are considered for the study.

In the summer of 2008, the experimental prototype was built in full scale as a built-in part of an office building of the Intemper company, located in one of the industrial parks of Colmenar Viejo.

The building has a rectangular floor plan and three stories. The first two have the same dimensions (13.8 m × 32.5 m), whereas the third one (13.8 m × 32.5 m) shows a terrace facing South where the experimental prototype is installed as a built-in part of the façade. Both during the summer and the winter, the façade is fully sunlit, since the plot has a wide open space in its front part and the closest constructions are located far enough to avoid drop shadows (Fig. 1). The prototype consists of four spaces with same dimension (1.8 m × 1.8 m × 2.4 m) and enclosure composition, differing only in the enclosure corresponding to the South façade (Fig. 2).

The four spaces are completely isolated from each other, since one of the design objectives was to create virtually adiabatic spaces, so that all the heat transfers took place only and exclusively through the façade. Because of this, a 0.6 m layer of extruded polystyrene $\lambda = 0.035$ W/(m K) was added to the floor, roof and walls of each environment, obtaining a total thermal resistance of 17.8 m^2 K/W for the separation layers and 17.2 m^2 K/W for floor and roof. This research focuses on the analysis and comparison of the thermal data obtained through the monitoring of two of the prototype's four existing façades. Both envelopes are made up of modular panels which include the following parts: metallic box (0.6 m × 0.6 m × 0.08 m), substrate, drip irrigation system, coupling structure and vertical structure. The exterior finishing of one of the panels corresponds to a sedum vegetation layer.

The façades are monitored so that the temperature data existing in each of the modules' enclosure layers can be obtained and recorded, from outdoors to indoors, through state probes. Two surface sensors are placed in both façades, one between the metal sheet and felt layer of the panel, the other behind the panel, in the interior surface. Two ambient temperature sensors are installed in the modules' interior, located in the central zone, near the floor and ceiling (Fig. 3).

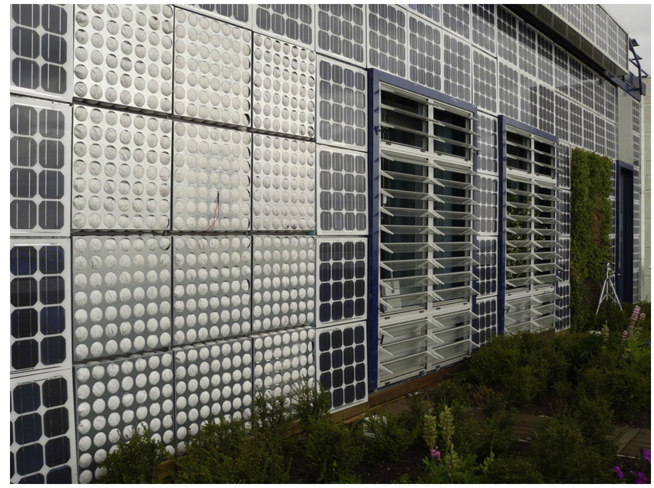

Fig. 1. Experimental façades.

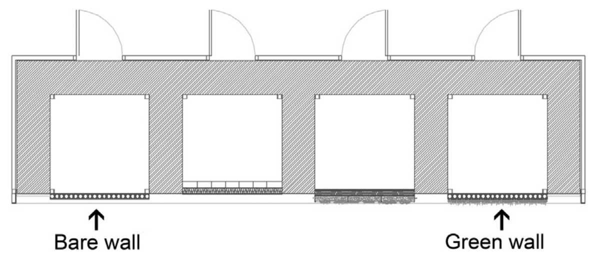

Fig. 2. Schematic plan of the full-size experimental prototype.

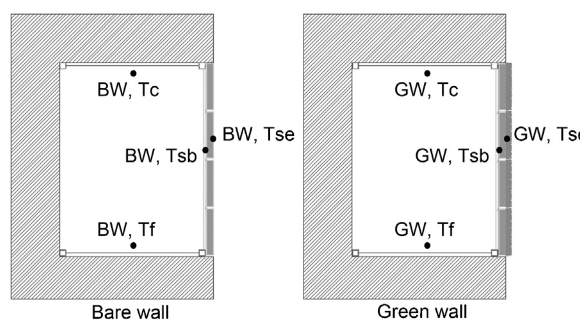

Fig. 3. Schematic section of the full-size experimental prototype and position of the temperature sensors.

Table 1
Local climate conditions during the monitoring period. The number of hours is given in percentage with respect to the whole period.

Temperature [°C]				
≤0	(0,10]	(10,20]	(20,30]	≥30
2.0	30.7	36.4	26.8	4.1
Relative humidity [%]				
≤20	(20,40]	(40,70]	≥70	
4	26.5	41.5	28.1	
Global horizontal irradiance [W/m^2]				
≤100	(100,400]	(400,800]	≥800	
25.9	30.7	30.3	13.1	

The thermal data obtained in the façades and analyzed in this work are:

- surface temperature of the metal sheet on the exterior (T_{se});
- surface temperature of the metal sheet on the interior (T_{si});
- air temperature near the ceiling (T_c);
- air temperature near the floor (T_f).

The data taken in the façade with vegetation are compared with those taken in the façade without vegetation. For each probe, values are taken every 5 min. These values are written down in a spreadsheet, indicating date and time. The momentary values can be graphically represented with the software used. The graph can contain the group of probes to be represented every moment, as well as the choice of the time period.

The software that records the data is Scada type, installed in a conventional PC.

The equipment that transforms the analogue signal of the probes into a temperature value is a type M-340 programmable automation equipment from Schneider.

In order to ensure that the reference façade have developed vegetation at all times, spare modules with enough plants as to replace the modules in case of vegetation loss are prepared.

PT100 thermoresistances (63 mm × 8 mm × 2 mm) in three threads are used to obtain the surface temperature of each component of the enclosure.

The thermoresistances are doubled in order to verify the reliability of the recorded data in all cases. This duplication prevents possible reinstallations in case of errors in the thermoresistances, because of breakage or other causes.

For the rest of data (solar radiation, pluviometry, wind speed in the exterior ambient, relative humidity in the exterior ambient), the information provided by the weather station, installed in another experimental building less than 100 m away from the façades, is used.

The accuracy of the probes is ±0.15 K for the thermoresistances and ±0.2 K and ±2% for the thermohygrometers.

3. Local climate conditions

During the three years of monitoring, the temperature fluctuates between 6 and 38 °C, the horizontal global irradiance rises above 1200 W/m^2 only twice, whereas the relative humidity varies considerably, fluctuating between 20% and 100% (it is below 20% for only 4% of the time). As shown in Table 1, extreme temperatures are rarely recorded: below 0 °C in 2% of the cases and over 30 °C in 4.1% of the cases.

In fact, the temperature varies between 10 and 20 °C for 36.4% of the recorded hours, between 0 and 10 °C for 30.7% and between 20 and 30 °C for 26.8%.

Concerning the relative humidity, in 30.5% of the cases it is below 40%, and in 42.6% it is over 60%, and only in 26.8% of the cases it is placed within the considered comfort range, between 40% and 60%.

Analysing the data relating to horizontal irradiance, if the night-time hours are discarded (44.9% of the total) and only the hours with irradiance values over zero are considered, the hours including twilight and dawn (irradiance < 100 W/m^2) represent approximately a quarter of the data.

During most of the daytime hours, values between 100 and 800 W/m^2 are registered. Based on these values, 30.7% is between 100 and 400 W/m^2 and 30.3% between 400 and 800 W/m^2, respectively. Only 13.1% of the hours does the irradiance rise above 800 W/m^2.

Fig. 4 shows how during the three years of the study the evolution of the daily minimum and maximum temperatures is similar.

During the summer periods, the minimum temperatures in most cases do not go below 15 °C, whereas the maximum temperatures

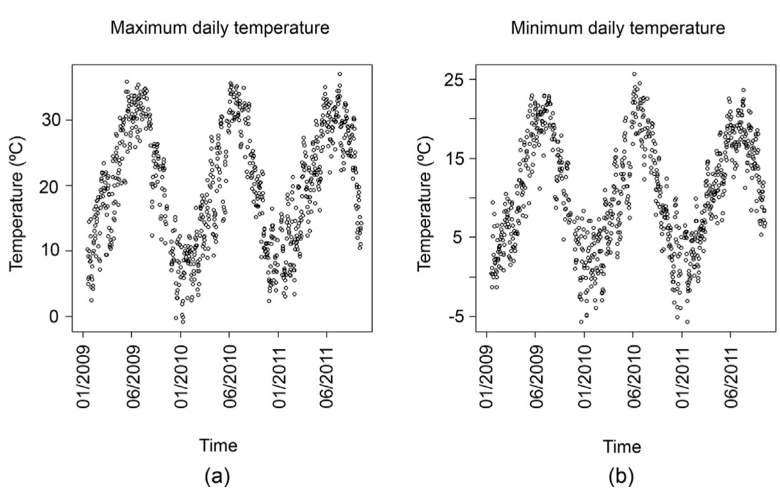

Fig. 4. Evolution of the daily maximum (a) and minimum (b) temperatures.

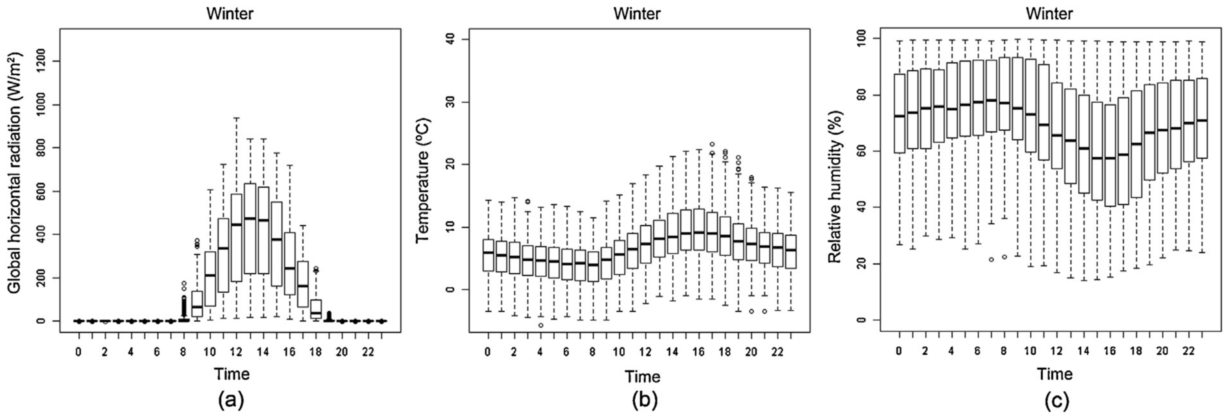

Fig. 5. Multiple box-plot for the hourly evolution of the exterior horizontal global irradiance (a), temperature (b) and relative humidity (c) in the winter.

rise above 30 °C often. The highest minimum temperatures are recorded during the summer of 2010, whereas the highest maximum temperatures are recorded during the summer of 2011.

Regarding the winter periods, during January and February of 2010 and 2011 the lowest minimum temperatures are recorded, whereas the lowest maximum temperatures are recorded in December 2009.

In order to carry out a more detailed study on the climatic conditions during the different seasons of the year, the data was grouped by date in four categories: winter, spring, autumn and summer.

In each of them, the data corresponding to a season during the three years were analyzed, so that each category gathers the characteristics of the season analyzed over the full study period.

To this end, a box-plot is used, which is a graphic representation very generalised within statistical studies that enables to observe the quartiles, the maximum and minimum, once the outliers have been removed [30]. This way, separating the outlier observations, a centrality measure (the median), two dispersion measures (the interquartile range and the range) and the possible symmetry of the sample can be noted.

The k percentile of a sample is defined as the value leaving *k*% of the observations below. In the box-plot 5 percentiles are represented:

- the minimum or percentile zero;
- percentile 25 which is the one leaving 25% of the sample below, also known as first quartile, Q1;
- percentile 50 which is the one leaving 50% below, also known as second quartile or median, Q2;
- percentile 75 which is the one leaving 75% below, also known as third quartile, Q3;
- the maximum or percentile 100.

For the completion of the graph, a box is drawn; its superior and inferior sides correspond with the first and third quartile. This box is divided by a segment, the median. The distance between the first and third quartile is called interquartile range (RI).

In order to calculate the whiskers, 1.5RI is subtracted to the first quartile and 1.5RI is added to the third quartile. Any value under $Q1 - 1.5RI$ or over $Q3 + 1.5RI$ is considered outlier. The whiskers represent the minimum and maximum values once the outlier values have been removed.

This representation has the advantage of being robust (influenced very little by outlier values), it separates and represents the outlier values, draws the position of the five most relevant percentiles, gives an idea of the dispersion of the data without taking into account the outlier values and determines the possible symmetry of the sample.

3.1. Winter

During the winter (Fig. 5a), positive irradiance values are recorded between 8:00am and 6:00pm, with the maximum value around 1:00pm and coincidental with the summer peak, too (Fig. 6a). During the morning and the evening, the data variability is low, whereas in the central hours of the day it is notably high.

Although the median's maximum value rarely surpasses 400 W/m^2 there are sunny days recorded in which the irradiance during the central hours of the day reaches 700 W/m^2.

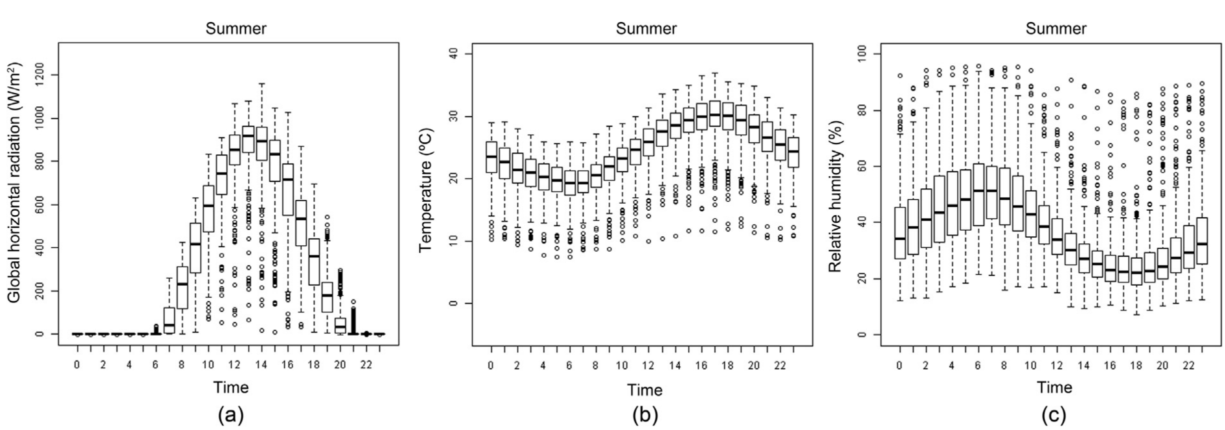

Fig. 6. Multiple box-plot for the hourly evolution of the exterior horizontal global irradiance (a), temperature (b) and relative humidity (c) in the summer.

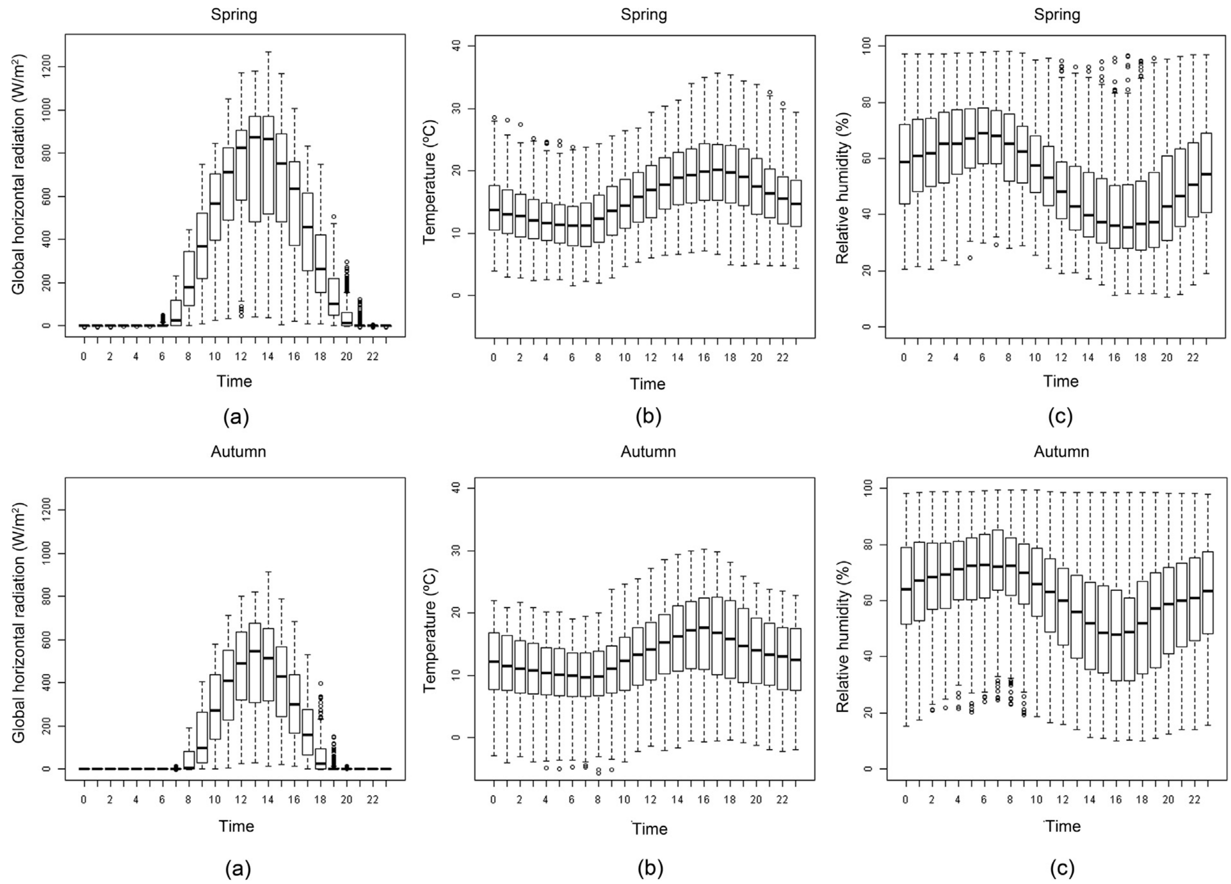

Fig. 7. Multiple box-plot for the hourly evolution of the exterior horizontal global irradiance (a), temperature (b) and relative humidity (c) in the spring and the autumn.

The highest temperatures (Fig. 5b) are reached between 3:00pm and 5:00pm, the lowest ones between 6:00am and 8:00am. The data varies notably during the evening hours, with a slight reduction of this variation during the night and the morning. The median fluctuates between 4 and 8 °C and, dismissing the outlier values, the rest of the temperatures vary between −5 and 22 °C. The lowest relative humidities (Fig. 5c) are recorded during the night and the highest ones during the warmest hours of the day. Even though the data present a high variability, the median oscillates between 60% and 80%.

3.2. Summer

During the summer (Fig. 6a), there is an average of 5 more sun hours than during the winter: positive irradiance values start to be recorded around 6:00am and daylight lasts until 9:00pm.

Although the median never surpasses 900 W/m^2, the irradiance values surpass 1000 W/m^2 in several occasions between 1:00pm and 2:00pm. The variability of data between 1:00pm and 6:00pm is higher than in the rest of hours of the day.

Concerning the temperatures (Fig. 6b), the data are notably less concentrated with respect to the winter, the median fluctuates between 20 and 30 °C and practically during all hours of the day the variability of the data is approximately of 15 °C. There are records of temperature peaks over 35 °C and outlier values below 10 °C. The relative humidity (Fig. 6c) presents as well a high variability. From noon until twilight practically all the values are below 50% and the median varies between 20% and 40%, reaching their minimum around 6:00pm. During the nighttime hours and the first hours of the morning the relative humidity is significantly higher, although in all the hours of the day 75% of the recorded data never surpasses 60% of relative humidity.

3.3. Spring and autumn

Comparing the intermediate seasons, we can notice that in all the hours of the day the irradiance is, during the spring, higher in average than the irradiance during the autumn (Fig. 7a). In addition, the variability during the spring is quite higher than during the autumn.

From 12:00pm to 2:00pm the irradiance stays practically constant during the spring, whereas during the autumn, like in the rest of the seasons, the maximum peak is reached around 1:00pm. However, the temperatures (Fig. 7b) vary quite more in the autumn than in the spring, particularly during the evening and the night. During the spring, the temperatures are slightly gentler than during the autumn, oscillating between 12 and 20 °C in spring and between 10 and 18 °C in autumn. The median of the relative humidity (Fig. 7c) in both seasons presents its maximum around 70% right before the sunrise and its minimum around 5:00pm at 35% in spring and 45% in autumn. Half of the data oscillates approximately between 35% and 80% and their variability is higher in the autumn than in the spring, with noticeable higher differences during the evening hours principally.

4. Experimental sessions

The panels with vegetation, previously cultivated in a nursery, were mounted on the experimental building completely developed.

Table 2
Relative frequencies in percentage of the combination of temperature and relative humidity during the three years studied.

	Temperature [°C]						
RH [%]	≤5	(5,10]	(10,15]	(15,20]	(20,25]	≥25	Sum
(0,40]	0.4	0.7	2.0	4.6	9.2	13.6	30.5
(40,70]	4.8	7.7	9.7	11.4	7.0	0.9	41.5
(70,100]	7.2	11.9	6.8	2.0	0.1	0.0	28.0
Sum	12.4	20.3	18.5	17.9	16.4	14.5	100.0

Table 3
Average value and standard deviation (in brackets) of the temperature differences recorded by the sensors located in the same position in both modules, for the most frequent cases of the combination of exterior temperature and relative humidity.

T [°C] RH [%]	≤5 (70,100]	(5,10] (40,70]	(5,10] (70,100]	(10,15] (40,70]	(10,15] (70,100]	(15,20] (40,70]	(20,25] (0,40]	(20,25] (40,70]	≥25 (0,40]
Ext.	−0.93 (3.48)	2.79 (9.64)	−0.02 (4.42)	4.05 (9.82)	0.60 (5.47)	4.37 (9.05)	8.62 (10.98)	5.80 (7.89)	13.83 (9.52)
Int.	−0.26 (1.24)	1.99 (2.73)	0.55 (1.26)	2.62 (2.51)	1.27 (1.50)	3.47 (2.16)	6.26 (2.86)	4.84 (2.04)	8.62 (2.68)
Floor	0.45 (0.80)	1.86 (1.04)	0.90 (0.77)	2.21 (1.15)	1.30 (0.88)	2.92 (1.23)	4.51 (1.30)	3.86 (1.08)	5.37 (1.28)
Ceiling	0.80 (0.83)	2.50 (1.34)	1.24 (0.81)	2.76 (1.38)	1.65 (0.93)	3.35 (1.29)	5.03 (1.60)	4.08 (1.15)	5.99 (1.64)

For this reason, the data-collection system started providing reliable data from the beginning of the monitoring, in November 2008. This study analyses the data collected from 1 January 2009 to 8 November 2011.

The great amount of data provided by the data-collection systems prompted the use of statistical data processing.

The monitoring results are described below. The temperatures recorded by the thermoresistances located in the same position in both modules are compared in all cases.

Since the interest lies in the performance of the module with vegetation as opposed to the module without it, instead of analyzing separately the temperatures in each module, the difference of temperature recorded each moment between the module with no vegetation and the module with vegetation is analyzed. This difference is considered as variable.

Table 2 presents the relative frequencies of the combination of outdoor temperature and outdoor relative humidity during the three years studied.

The temperature difference for the most frequent cases (more than 75% of cases) is analyzed. Table 3 shows the average values of aforesaid variable, appearing below the mean (in brackets), its standard deviation.

Furthermore, the four thermoresistances by month are also studied.

In the following paragraphs, the behavior of the four variables in the four most representative months for each case is assessed.

4.1. Exterior surface temperature

Observing the exterior surface temperature (Fig. 8) it is noticeable that its performance is quite different during the night and the day. The fact is that, most of the months, during the night, the module without vegetation records a temperature lower than 1–2 °C with respect to the module with vegetation.

Conversely, the temperature in the module without vegetation during the day is considerably higher than the temperature in the module with vegetation. The difference grows as the solar radiation rises, recording its maximum peak around 2:00pm.

In addition, during the night the data appear concentrated, whereas during the day they are significantly more dispersed.

During June, July and August, the performance at night is different with respect to the rest of months of the year.

In fact, in those months the temperature in the module without vegetation stays higher than that of the module with vegetation, both at night and during the day. In the nighttime hours, the differences are very small, with the median barely higher than 0 °C However, during the warmer hours of the day, it oscillates between 20 and 25 °C Also, during the daytime hours, 50% of the data are within 15 and 30 °C with peaks of more than a 40 °C difference.

Finally, the dispersion of the data during the daytime hours is significantly higher in the cold months than in the warm months.

From these first results, it follows that the thermo-regulation effect of the vegetation is particularly beneficial during the summer, with a higher reduction of temperature during the hours with a higher solar radiation.

4.2. Interior surface temperature

Analyzing the interior surface temperature (Fig. 9), it's noticeable how the thermal inertia of the panel influences the attenuation of the differences between the two modules.

During the nighttime hours of the months with lower radiations, the differences of temperature between the modules are barely noticeable. If those differences happen, it's in the module without vegetation where the lowest temperatures are recorded. During the day, the opposite situation occurs. The median of the differences is positive although its value is very low, fluctuating between 0 and 5 °C.

In the daytime hours, the data are quite scattered, whereas in the nighttime hours they are very concentrated. This effect is positive for the heat balance of the façade, because in the colder months of the year, the additional vegetation layer makes the surface temperature in the module with vegetation during the coldest moment of the day (night) slightly higher than the surface temperature in the module without vegetation.

From May to August, the temperature in the module without vegetation is mostly (more than 99% of times) higher than in the module with vegetation. The smaller difference is recorded just before dawn, in the coldest moment of the day, whereas the greatest differences occur between 4:00pm and 6:00pm. The variation range of the median is between 1 and 11 °C, and an important concentration of data around the median stands out, symmetrical during the day.

In the central months of spring and autumn, the temperature of the module without vegetation during the day is always higher than that of the module with vegetation. The median varies between 5 and 12 °C, but the data are more dispersed than in the summer months.

In most cases, during the night the temperature in the module with vegetation is also lower than in the module without vegetation, although in 15% of the cases the situation is the opposite. The differences detected are quite small, the median never surpasses 4 °C. The values are constant during all the nighttime hours, spreading generally in a symmetrical and concentrated way.

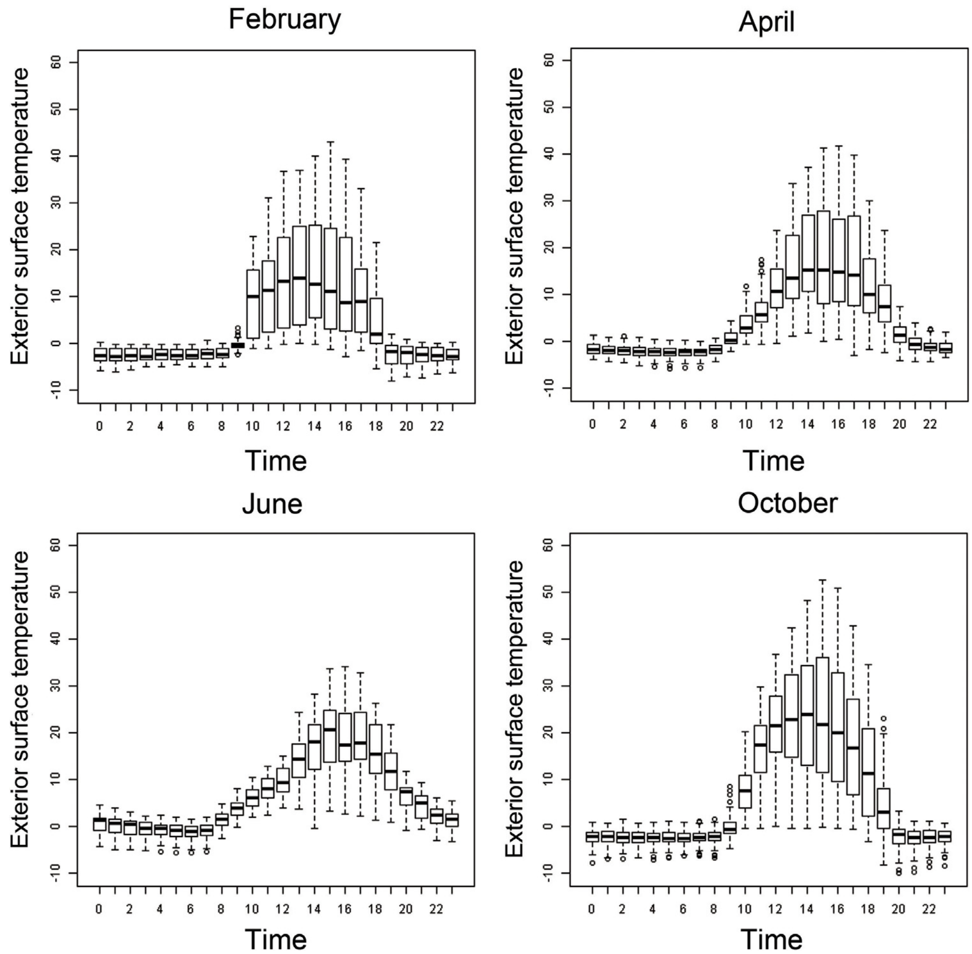

Fig. 8. Hourly evolution of the temperature difference (°C) in the exterior surface of the panel in four reference months.

On the whole, even though the effect of the vegetation is reduced by the thermal inertia of the panel, there is still a noticeably great difference between the two modules. In addition, the presence of vegetation leads to a bigger drop of the interior temperature of the panel during the evening of the summer months, representing normally the most critical moment of the whole year due to the overheating of the exterior surfaces.

4.3. Interior temperature

Despite noticing certain differences, the results obtained in the interior surface show a tendency parallel to the behavior of the air temperature measured near the floor and near the ceiling (Fig. 10).

During practically all the months, the ceiling and floor graphs are quite similar although the differences between the two modules observed in the ceiling are greater than those observed in the floor.

Throughout the measurement period, it can be noticed that the median is always positive. In fact, the 75% of the data for each time slot is positive except in December and January. Once again, the highest differences are recorded during the day.

In the winter months, during the night the data are more concentrated than during the day. The median varies between 0 and 2 °C and is practically constant during the night.

In the summer, the differences between the two modules are greater, the median oscillates between 2 and 7 °C and there is a higher concentration of data than during the winter, particularly in the daytime hours. During the evenings of July and August, the median never goes below 6 °C and differences from 8 to 10 °C are recorded between the two modules in 25% of the cases.

In the spring and autumn months, similar results during the day to those recorded in the summer are obtained. This is probably due to the fact that these months are characterized by high irradiance values in the vertical surface facing south. On the other hand, the variability in the weather conditions causes the data to be notably more dispersed than those recorded in the summer, both during the day and during the night.

In conclusion, it can be stated that the presence of vegetation in the exterior surface of the module results in a considerable reduction of the interior temperatures, particularly during the daytime hours. In the warmer moments of the year, the evenings of July and August, the difference of temperature between the two modules is practically constant and reaches its maximum values. This fact is probably the result of the effect of the plants' evapotranspiration, more effective when the relative humidity level in the exterior reaches minimum values. The effect of the vegetation is also noticeable in the months in which the irradiance on the vertical surface facing south is very high. Under these conditions, the plants act as a shadowing element that manages to reduce in several degrees the temperature in the interior of the modules, by preventing the overheating of the exterior surface.

5. The autoregressive fitted model

In order to carry out the description and prediction of the difference of temperature between the module without vegetation and the module with vegetation, the relation of this variable with respect to the exterior climate conditions is assessed. In this case,

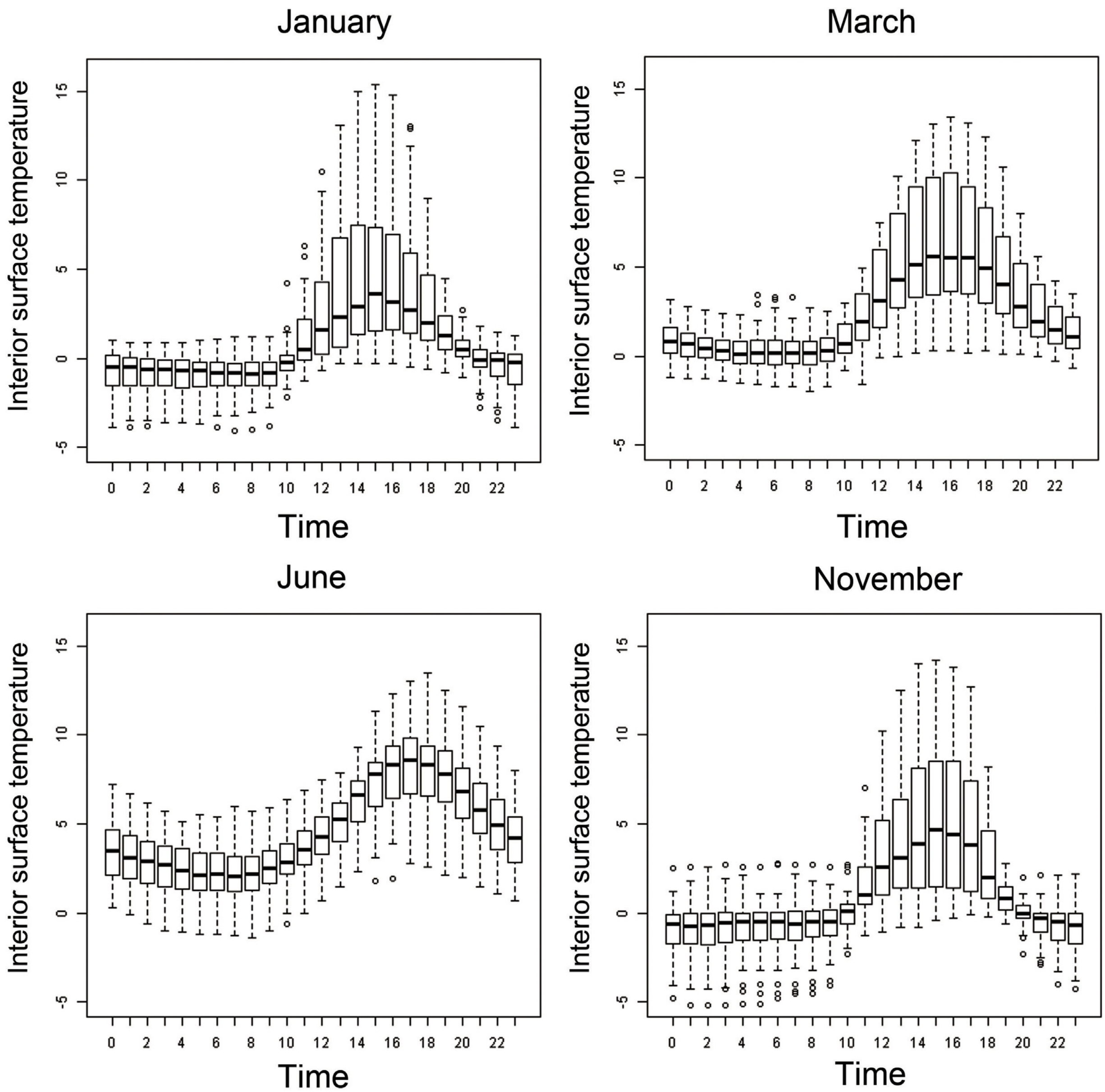

Fig. 9. Hourly evolution of the temperature difference (°C) in the interior surface of the panel in four reference months.

its behavior based on the outdoor temperature, the outdoor relative humidity and the vertical irradiance on a surface facing south are studied. These three variables are the input variables of the model and the natural way of studying these dependences is by means of the linear regression models, that is, expressing the difference of temperature of the modules as a linear combination of the exogenous variables [31,32]. The fact that none of the four variables have independent observations, since they are observed throughout time, makes it necessary to adjust the parameters by an autoregressive model with exogenous variables. This is nothing more than multiple linear regression model in which the delays of the dependent variable and the input variables are introduced as input variables. For a more comprehensive study of this type of models, see Shumway and Stoffer [33]. That is, we adjust a model of the type:

$$y_t = \beta_0 + \beta_1 y_{t-1} + \beta_2 y_{t-2} + \beta_3 \theta_t + \beta_4 \theta_{t-1} + \beta_5 H_t + \beta_6 H_{t-1} + \beta_7 I_t + \beta_8 I_{t-1} + \varepsilon_t \quad (1)$$

where the subscript t refers to the time t measured in hours, from $t = 1, \ldots T$, $T = 25{,}008$ which are the hours observed from 00:00am of 1 January 2009 to 11:00pm of 8 November 2011.

The variable y_t is the difference of temperature between the module without vegetation and the module with vegetations at time t, θ_t is the outdoor air temperature, H_t is the outdoor air relative humidity and I_t is the global irradiance on the vertical surface facing south. The parameters of the model β_i, $i = 0, \ldots, 9$ are estimated ($\hat{\beta}_i$), so that the residual sum of squares is minimized like in the linear regression model. The residues of the model ε_t are white noise, that is, $\varepsilon_t \sim N(0, \sigma)$ with σ constant. The goodness of fit of the model is measured with the multiple R-squared (R^2).

Due to the heterogeneity of the data and the great amount of missing data, and in order to facilitate the interpretation of the model, the time slots with a similar thermal performance are grouped. This way, the post-midnight values (01:00am to 06:00am), morning values (07:00am to 10:00am), midday values (from 11:00am to 2:00pm) evening values (from 3:00pm to 6:00pm) and night values, pre-midnight (from 7:00pm to

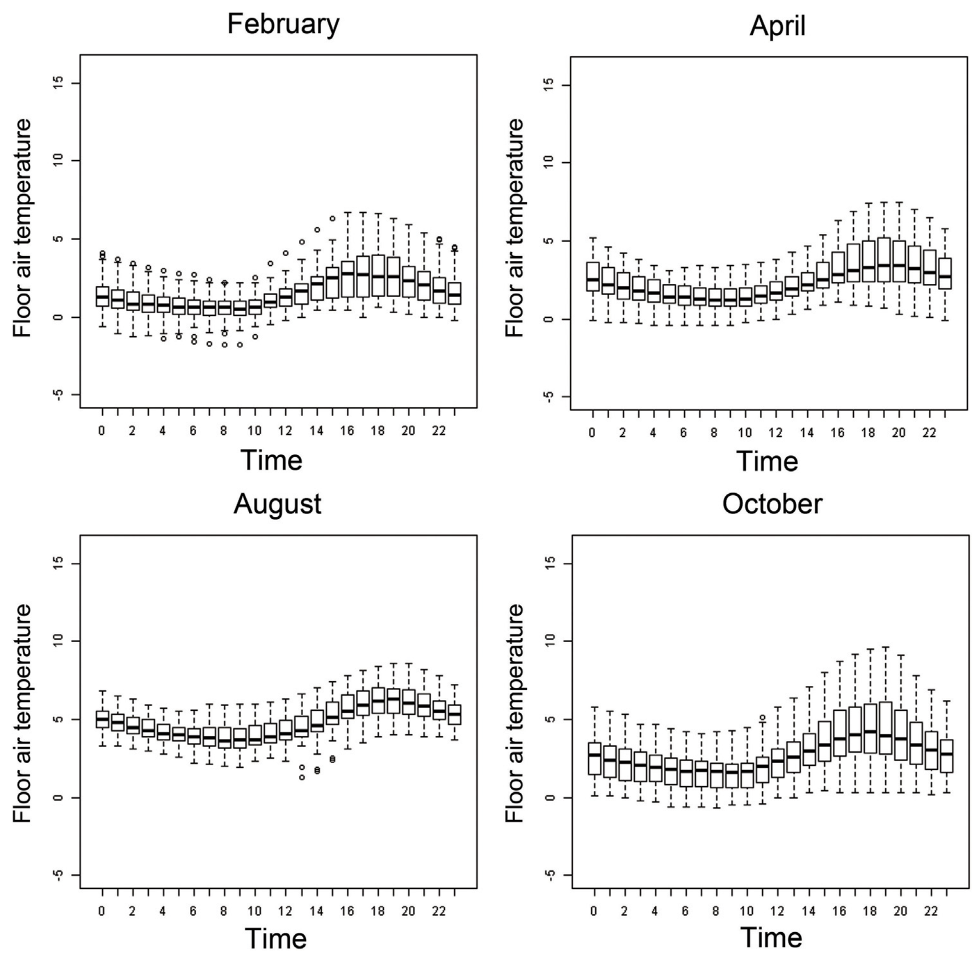

Fig. 10. Hourly evolution of the air temperature difference (°C) in the module's interior near the floor in four reference months.

Table 4
Estimated parameters and multiple R-squared for each one of the four sensors and the five time periods analysed. M = morning, MD = midday, E = evening, PrMD = pre-midnight, PoMD = post-midnight, F = floor, C = ceiling, I = interior surface, E = exterior surface.

Time	Position	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	$\hat{\beta}_5$	$\hat{\beta}_6$	$\hat{\beta}_7$	$\hat{\beta}_8$	R^2
M	F	0.73	0.58	0.10	0.13	−0.09	0	−0.01	0	0	0.85
M	C	1.06	0.54	0.14	0.10	−0.07	−0.006	−0.007	0	0	0.84
M	I	0.46	0.45	0.16	0.19	−0.11	0	−0.013	0	0	0.79
M	E	0.98	0.62	0.11	0.22	−0.21	−0.021	−0.013	0.016	−0.013	0.63
MD	F	0.79	0.58	0.10	0.05	−0.028	−0.008	−0.004	0.0007	−0.0004	0.84
MD	C	1.89	0.65	0.09	0.11	−0.099	−0.025	0	0.005	−0.003	0.82
MD	I	1.89	0.65	0.093	0.11	−0.099	−0.025	0	0.005	−0.003	0.82
MD	E	4.16	0.78	0.032	0.15	−0.21	−0.095	0.050	0.024	−0.020	0.84
E	F	1.53	0.74	0	0.042	−0.031	−0.033	−0.016	0	0	0.86
E	C	2.33	0.69	0.067	0.096	−0.098	−0.054	0.029	0	0	0.84
E	I	3.53	0.63	0.13	0.12	−0.12	−0.091	0.052	0	0	0.85
E	E	3.93	0.65	0.12	0.15	−0.17	−0.136	0.088	0.017	−0.013	0.82
PrMD	F	1.22	0.81	0	0.055	−0.047	−0.030	−0.017	0	0	0.92
PrMD	C	1.35	0.81	0	0.035	−0.031	−0.036	−0.022	0	0	0.90
PrMD	I	0.96	0.70	0.12	0.16	−0.13	−0.021	0.008	0	0	0.94
PrMD	E	−0.64	0.66	0.16	0.33	−0.28	−0.02	−0.02	0	0	0.87
PoMD	F	0.97	0.64	0.11	0.13	−0.10	−0.006	−0.006	0	0	0.91
PoMD	C	1.09	0.64	0.10	0.09	−0.07	−0.01	0	0	0	0.90
PoMD	I	0.51	0.61	0.12	0.22	−0.17	0.006	−0.018	0	0	0.90
PoMD	E	−1.04	0.60	0.09	0.36	−0.31	0.02	−0.02	0	0	0.70

11:00pm), have been averaged for each variable. The models have been considered for each of the five time slots and for each of the four sensors, obtaining the following results (Table 4).

The last column shows the multiple R-squared (R^2) of the estimated models.

It measures which variability percentage of the variable "difference of temperature between the modules without vegetal panel and with vegetal panel" is explained with the model used. As it can be observed, these coefficients are very high, with values around 85% of the explained variability for the daytime

Table 5
Coefficients calculated for the estimation of the average expected value. *M* = morning, MD = midday, E = evening, PrMD = pre-midnight, PoMD = post-midnight, F = floor, C = ceiling, I = interior surface, E = exterior surface.

Time	Position	$\hat{\alpha}_0$	$\hat{\alpha}_1$	$\hat{\alpha}_2$	$\hat{\alpha}_3$
M	F	2.34	0.13	−0.035	0
M	C	3.31	0.10	−0.041	0
M	I	1.17	0.19	−0.033	0
M	E	3.63	0.014	−0.047	0.01
MD	F	2.52	0.095	−0.038	0.0009
MD	C	3.40	0.059	−0.043	0.0028
MD	I	7.38	0.041	−0.098	0.005
MD	E	22.57	−0.289	−0.243	0.025
E	F	6.01	0.041	−0.068	0
E	C	9.54	−0.010	−0.100	0
E	I	14.65	−0.010	−0.162	0
E	E	17.90	−0.056	−0.216	0.019
PrMD	F	6.36	0.043	−0.070	0
PrMD	C	0.837	−0.069	−0.023	0
PrMD	I	5.63	0.124	−0.081	0
PrMD	E	−3.78	0.274	−0.003	0
PoMD	F	3.86	0.114	−0.050	0
PoMD	C	4.41	0.090	−0.049	0
PoMD	I	1.93	0.184	−0.044	0
PoMD	E	−3.42	0.150	0.0004	0

Table 6
Residual standard error $\left(\hat{\sigma}^2\right)$ of the estimated models expressed in $^\circ C^2$.

	Morning	Midday	Evening	Pre-midnight	Post-midnight
Floor	0.60	0.61	0.69	0.53	0.49
Ceiling	0.58	1.16	0.97	0.60	0.48
Interior surface	0.97	1.16	1.50	0.68	0.64
Exterior surface	1.27	3.54	4.12	1.17	0.90

periods and 90% of the explained variability for the nighttime periods.

In addition, for each one of the periods, the sensor of the exterior metal sheet layer is the one presenting the worst adjustment out of the four models, except for the midday period, which presents a goodness of fit very similar to that of the other three sensors.

The coefficients relating to the irradiance ($\hat{\beta}_7$, $\hat{\beta}_8$) are only significant in the four thermoresistances during the daytime period relating to midday and in the exterior superficial thermoresistance in the morning and the evening. In all the cases, the coefficients have very low values and the delay in $t-2$ compensates for the delay value in $t-1$. That is to say, the coefficients $\hat{\beta}_7$, are small and positive and the coefficients $\hat{\beta}_8$, are negative and of a slightly smaller magnitude.

The dependency of the variable relative humidity is more heterogeneous, the coefficients that explain it ($\hat{\beta}_5$, $\hat{\beta}_6$) are generally negative and small in absolute value. This is interpreted as the humidity rectifying the influence of the most important variable, the exterior temperature, and the higher the humidity, the smaller the difference of temperature between the module without vegetation and the module with vegetation.

The coefficients relating to the way the outdoor temperature (θ_t) affects the difference of temperature between modules y_t, ($\hat{\beta}_3$, $\hat{\beta}_4$) have a higher value, the coefficient relating to the day temperature ($\hat{\beta}_3$) is positive and high (the higher the temperature, the greater the difference of temperature between the modules), whereas the coefficient relating to the temperature of the previous day is smaller in absolute value and negative.

Finally, the coefficients ($\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\beta}_2$) are those relating to the auto-regressive part of the model, that is, they are the parameters of the linear regression of y_t over their delays. They explain how the temperature difference in time t, y_t, depends on the values of the temperature difference in times $t-1$ and $t-2$: all the estimated coefficients are relatively big and positives (except the two $\hat{\beta}_0$ of the thermoresistance of the exterior panel during the nighttime periods).

6. Results and discussion

6.1. The predictive numerical model

The parameters β_i, $i = 0, \ldots, 9$ of the autoregressive models make possible the prediction of future observations y_{t+1}, given the observations up to time t. In addition, in this article the estimated parameters are used to study the average behavior of the modules' difference of temperature dependingon the expected values of the outdoor temperature, $E\left(\theta_t\right)$, relative air humidity in the exterior, $E(H_t)$, and global irradiance on vertical surface facing south $E(I_t)$. The property stating that the studied series are stationary is used, hence the mean function, $E(x_t)$, of a stationary time series is independent of time t we will write $E(y_t) = \mu_t$, $E\left(\theta_t\right) = \mu_0$, $E(H_t) = \mu_H$ and $E(I_t) = \mu_I$ Taking mean functions in Equation 2.

$$E(y_t) = \beta_0 + \beta_1 E(y_{t-1}) + \beta_2 E(y_{t-2}) + \beta_3 E\left(\theta_t\right) + \beta_4 E\left(\theta_{t-1}\right) + \beta_5 E(H_t) + \beta_6 E(H_{t-1}) + \beta_7 E(I_t) + \beta_8 E(I_{t-1}) \quad (2)$$

so that the average expected value of the difference of temperature between the module without vegetation and the module with vegetation can be estimated, taking into account the average outdoor temperature, the average humidity and the average irradiance in that period of the day (Eq.(3)).

$$E(y_t) = \alpha_0 + \alpha_1 \mu_\theta + \alpha_2 \mu_H + \alpha_3 \mu_I \quad (3)$$

where the estimation of the parameters $\hat{\alpha}_0$, $\hat{\alpha}_1$, $\hat{\alpha}_2$ y $\hat{\alpha}_3$, is obtained from the estimation by squared minimums of the β_i parameters.

$$\hat{\alpha}_0 = \frac{\hat{\beta}_0}{1 - \hat{\beta}_1 - \hat{\beta}_2}$$

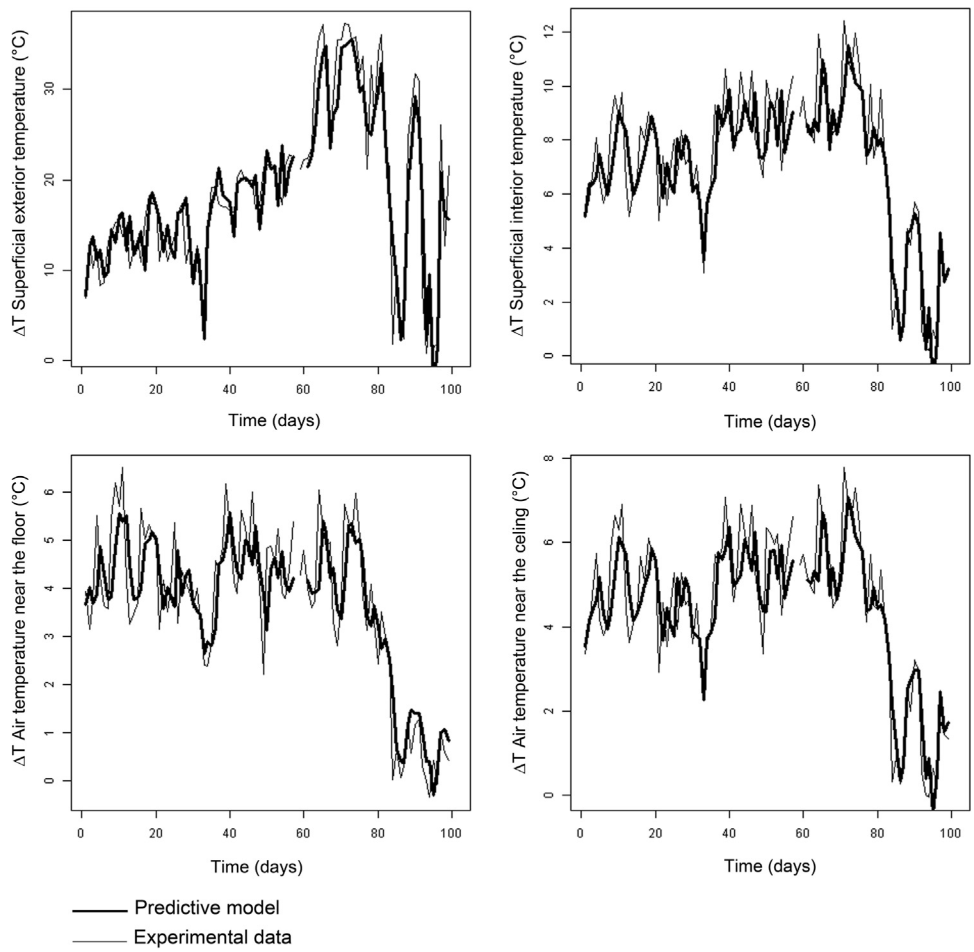

Fig. 11. Data observed and adjustment done of the last 100 days for the midday models.

$$\hat{\alpha}_1 = \frac{\hat{\beta}_3 + \hat{\beta}_4}{1 - \hat{\beta}_1 - \hat{\beta}_2}$$

$$\hat{\alpha}_2 = \frac{\hat{\beta}_5 + \hat{\beta}_6}{1 - \hat{\beta}_1 - \hat{\beta}_2}$$

$$\hat{\alpha}_3 = \frac{\hat{\beta}_7 + \hat{\beta}_8}{1 - \hat{\beta}_1 - \hat{\beta}_2}$$

Table 5 shows the coefficients estimated for the expected values obtained from the estimations of the autoregressive model (Eq.(1)). The table shows all the values obtained, but the estimated parameters in the case of the exterior sheet metal layer thermoresistance are omitted in order to study the performance.

The coefficients $\hat{\alpha}_0$ are positive values, particularly large in the case of the midday and evening periods for the exterior metal sheet layer thermoresistance and only negative in the cases of that same sensor during the nighttime periods. In general, in the linear models, $\hat{\alpha}_0$ measures the difference of temperature when the rest of the variables takes a zero value, but in our case there is no sense in studying the behavior with temperature 0, relative humidity 0% and irradiance 0 W/m^2.

The parameter $\hat{\alpha}_1$ measures the increase in the difference of temperature when the exterior temperature rises one degree and the rest of the variables stay constant. In most cases, this coefficient is positive, with values between 0.041 and 0.19.

For this value range, an increase in the exterior temperature of 1 °C implies that the module without vegetal panel takes values between 0.041 °C and 0.019 °C higher than the module with vegetal panel. The cases in which this coefficient is not within this value range correspond mainly to the exterior panel thermoresistance and to corrections of the parameter with a very high estimated value.

The coefficients $\hat{\alpha}_2$ measure the increase of the difference of temperature when the humidity rises 1% and the rest of the variables stay constant. In order to take a more suitable measurement unit, 10 $\hat{\alpha}_2$ measures this same increase when the humidity rises 10%. In all cases, except the last one corresponding to the exterior panel, it is a negative and small value, which means that the increase of the humidity implies a reduction of the difference of temperature between 0.23 and 1.62 °C.

Finally, the irradiance is only relevant in the midday hours (and for the exterior panel in the morning and evening). $\hat{\alpha}_3$ values are positive and with a very small absolute value. These values fluctuate between 0.09 and 5 °C.

6.2. Analysis of results of the predictive model

Observing the results of the models, it is noticeable how in all cases, during the night and the morning, a reduction of the relative exterior air humidity causes an increase in the difference of temperature between the module without vegetation and the module with vegetation. Similarly, a rise of the exterior temperature causes in practically all the cases an increase in the difference of temperature between the modules. The only exception is represented by the interior air near the ceiling, whose behavior is not constant. In fact, while the effect of the variation of the exterior relative humidity is the same than in the other points of the module, this is not the case for the effect of the variation of the outdoor temperature. Between 7:00pm and 11:00pm, a rise of the outdoor temperature causes a reduction in the difference of temperature between the modules, as opposed to what happens in most of the cases. The non-existent effect of the irradiance occurs because until 10:00am there is practically no direct solar radiation in the surface analyzed.

Conversely, the variable irradiance gains relevance in the explanation of the models relating to the central hours of the day. It is noticeable how its influence is more significant in the difference of temperature measured in the exterior surface of the modules and less significant in the difference of temperature recorded in the interior air. In addition, it is possible to observe how in this same time slot, both a rise of the outdoor temperature as well as a reduction of the exterior relative humidity, prompt in most of the cases an increase in the difference of temperature between the two modules. The only exception is represented by the exterior surface temperature, whose difference between the two modules decreases as the air temperature rises. Even so, the high irradiance values recorded on the vertical surface facing south during this time slot make the influence of the variable irradiance quite greater in relation to the influence of the variable temperature. As a consequence, the module with vegetation always records a lower surface temperature than the one recorded in the module without vegetation.

Analysing the evening models, it is possible to note how the influence of the irradiance is only observed in the difference of exterior surface temperature. In all the cases, the relative humidity coefficients are very high, which means that in this time slot the influence of this variable is particularly important. When observing the exterior temperature coefficients, it is clear how in most cases they are negative, that is, a rise of the temperature would imply a reduction of the difference of temperature between the module without vegetation and the module with vegetation, which seems illogical according to the previous results. This can be explained considering, on one hand, that a rise of the exterior temperature always implies a reduction of the relative humidity. On the other hand, given that in this time slot the relative humidity coefficients are quite a lot higher than the temperature coefficients, the importance of the variation of relative humidity results notably greater when compared with the variation of temperature. As a result, in this time slot, the temperatures recorded are in most of the cases lower in the module with vegetation than in the module without vegetation.

7. Validation of the numerical model

For the validation of the fitted models, there is an estimation of the residual standard error $\left(\hat{\sigma}^2\right)$ of each one of the analyzed models in Section 5 (Table 6). The forecast error depends directly on it.

It is noticed that, like with the multiple *R*-squared, the worst values correspond to the exterior panel's thermoresistances. Other than these sensors, the estimations of the residual standard error are in almost all the cases under 1, with a slightly better performance in the models of the nighttime periods than in the daytime ones.

It is also noticeable that the models have a better performance in the floor's and ceiling's thermoresistances than in those located in the sheet metal layer.

Regarding the hours of the day, it is observed, in general, the better performance of the prediction for the nighttime models (Pre-midnight and post-midnight) and the worst performance of the predictions during the midday and evening periods. For an intermediate performance, midday, Fig. 11 shows the temperature of the four thermoresistances during the last 100 days of the study and the prediction done by the model.

As it can be seen, for the four thermoresistances, a good performance of the prediction is detected as well as a good adjustment to the abrupt drop of temperature having taken place in the last twenty days or even to the increase of the variability having occurred in the exterior metal sheet layer.

8. Conclusions

This research focuses on the characterization of the thermal performance of a space formed by an enclosure with a vegetal finish in comparison to an identical one formed by an enclosure with a metal finish. The study is carried out by means of analysis and comparison of the thermal data obtained through the monitoring of two experimental modules of the same dimension (1.8 m × 1.8 m × 2.4 m) and enclosure composition, except for the enclosure corresponding to the south façade, where in one case a *sedum* vegetation layer is added. The monitoring is carried out from 1 January 2009 to 8 November 2011. Given that the interest lies in the performance of the module with vegetation as opposed to the module without, the differences of temperature recorded in each moment between the two modules are analyzed.

The study proves that the module with vegetation records lower temperatures than the ones in the module without vegetation in most cases. This effect is intensified when the outdoor temperature increases, by reaching maximum values for outdoor temperatures over 25 °C and relative humidities below 40%. Under these typical summer conditions, a mean drop of temperature of 8.6 °C in the interior surface of the vegetal enclosure and about 5.5 °C inside are observed.

These results show the potential of vegetal façades in reducing the surface temperature of buildings situated in continental Mediterranean climate zones. Hence, this also means a reduction in energy consumption during summer and the consequent drop in demand for cooling.

During winter, although the mean temperatures in the module with vegetation are lower, the differences recorded are small and the data are rather more variable, even there are cases where the temperatures in the module with vegetation are higher than those in the module without vegetation.

The use of this kind of vegetal systems seems to be recommended in similar climate zones to the one studied, as the benefits relating to summer are considerably more significant in comparison to the possible disadvantages in winter conditions.

Once the monitoring results and the relation of these variables in relation to the exterior weather conditions have been studied, a predictive model for the difference of temperature between the module without vegetation and the module with vegetation was developed. With the aim to facilitate the interpretation of the model, the hours of the day with a similar thermal performance have been grouped, considering a total of five time slots. A model has been estimated for each of the five time slots and for each of the four sensors, resulting in a total of twenty models.

The models fitted make possible the estimation of the average behavior of the difference of temperature of the modules based on the average outdoor temperature, the average relative humidity and the average irradiance on vertical surface facing south in that period of the day.

This enables these models to be extended to the study of vegetal façades located in places with similar weather conditions to those characteristic of the place of study. It is possible to estimate the behavior of the enclosure and interior environment with only the data for outdoor temperature, relative humidity and irradiance. The verification of the validity of the models is done by comparing the experimental and predicted data

As Section 7 shows, the performance of the predictions is quite similar to that previously observed, being captured abrupt changes and instability of temperature in the prediction. In fact, both the residual standard error and the multiple *R*-squared of the estimated models indicate that the error made in the prediction is very small.

In conclusion and regarding the possibility of using the predictive models in other contexts, the following aspects are worth mentioning:

- the models reproduce the performance of an envelope with vegetal finish type *sedum* facing another with metal finish. For the cases in which the façades analyzed were of a different finish than the ones tested, the necessary adjustments should be done, considering the physical and optical properties of the reference façade, as well as the characteristics of the type of plant used in the vegetal façade.
- The study develops five groups of models grouping the time slots with a similar thermal behavior. When using the models in places characterized by weather conditions different to those studied, it is important to consider if the time slots match with the ones observed in the study case, and if this were not the case, to adapt them to the new conditions.
- The fact that one of the explanatory variables of the models is the irradiance on vertical surface facing south causes that, in the event of studying façades with other orientations, the part of the model relating to the irradiance needs to be adjusted, being more or less influential based on the façade's orientation.
- Finally, in the event of considering the application of the model to enclosures formed of several layers, the models relating to the interior surface temperature should be taken into account and used as a starting point to estimate the thermal performance in the interior of the building. To this end, the effect of the façade's additional layers should be assessed, which would not be a problem since, on one hand, the thermal properties of the conventional materials are known and, on the other hand, there would be no difficulty in rebuilding the thermal gradient in the other layers of the enclosure once the response of the vegetal layer to the exterior weather conditions is known.

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